

FEMTOSECOND SYNCHRONIZATION OF LASER SYSTEMS FOR THE LCLS*

J. M. Byrd[#], L. Doolittle, G. Huang, J. W. Staples, R. Wilcox, LBNL, Berkeley, CA, USA

J. Arthur, J. Frisch, W. White, SLAC, Menlo Park, CA, USA

Abstract

The scientific potential of femtosecond x-ray pulses at linac-driven free-electron lasers such as the Linac Coherent Light Source is tremendous. Time-resolved pump-probe experiments require a measure of the relative arrival time of each x-ray pulse with respect to the experimental pump laser. To achieve this, precise synchronization is required between the arrival time diagnostic and the laser, which are often separated by hundreds of meters. An optical timing system based on stabilized fiber links that has been developed for the LCLS to provide this synchronization. Preliminary results show synchronization of the stabilized links at the sub-10-femtosecond level and overall synchronization of the x-ray and pump laser of <50 fs. We present details of the implementation at LCLS and potential for future development.

INTRODUCTION

The next generation of accelerator-driven light sources will produce sub-100-fs high brightness x-ray pulses[1]. In particular, pump-probe experiments at these facilities require synchronization of pulsed lasers and x-rays from electron beam on sub-100 fs time scales over distances of a few hundred meters to several kilometers[2,3]. Pump-probe experiments at these facilities plan to use an x-ray “probe” to produce snapshots of atomic positions within a sample some time after it is excited with a laser “pump.”

Varying the time between pump and probe enables the recording of a “movie” of the dynamics in the sample, with a time resolution determined by the x-ray pulse length and the relative timing jitter and drift of pump and probe. For experiments that require minutes to hours to collect data, the relative drift of the pump and probe should be less than the x-ray pulse length.

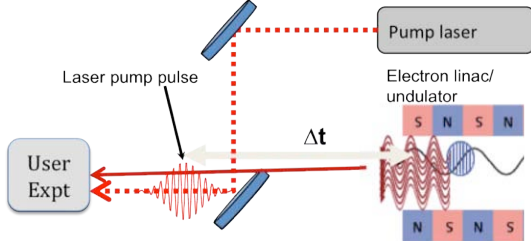


Figure 1: Layout for pump-probe timing.

One of the main challenges in reaching the level of synchronization required for pump-probe experiments is transmission of a timing signal over a relatively large facility. For example, in a facility of a kilometer in length, diurnal temperature variation results in cable length variation from several hundred ps to a nanosecond.

For the next generation of FELs, it is expected that the jitter of the electron beam with respect to the laser pump will be unacceptably large. Therefore, the goal is to measure the arrival time of each electron pulse with respect to the laser pump and allow the proper ordering of the “frames” of the movie. In this case, it is critical to synchronize the electron arrival time diagnostic with the pump laser.

STABILIZED RF SIGNAL DISTRIBUTION

One of the key features in any synchronization scheme is the ability to stably transmit a master clock signal to the remote clients with no uncontrolled relative timing drift between the clients. A schematic view of this distribution is shown in Fig. 2. The master oscillator signal is distributed over the accelerator to remote clients in a star configuration. Each link consists of a stabilized optical fiber with a second fiber carrying the error signal, a receiver for RF signal processing (RX), a synchronization head (S/H), and a remote client. The phase of the master signal is corrected at the end of each fiber link for the length variation of that link. Thus the relative timing drift

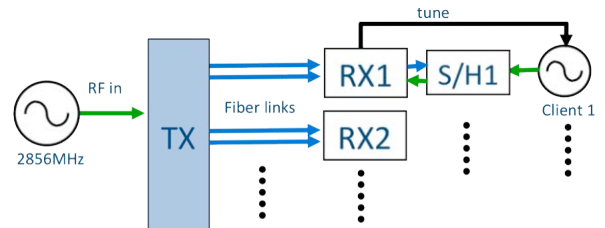


Figure 2: Schematic view of the distribution of the master clock over optical fiber. Each receiver consists of an RF signal processor (RX) and synchronization head (S/H).

of clients locked the master signal on independent fiber links does is minimized over many hours and even days.

Several approaches have been implemented to send stable signals over fiber optic links [4-8]. In our approach, each fiber link is an optical interferometer that precisely

*Work supported by by the U.S. Department of Energy under contract DE-AC02-05CH11231.

[#]JMByrd@lbl.gov

senses the delay variations in the link due to thermal variations of the fiber.

A schematic diagram of one of the stabilized RF transmission links is shown in Fig. 3. The fiber used for transmission is one arm of an interferometer, which tracks changes in the optical phase delay through the fiber. Variations in optical phase are observed at the receiver,

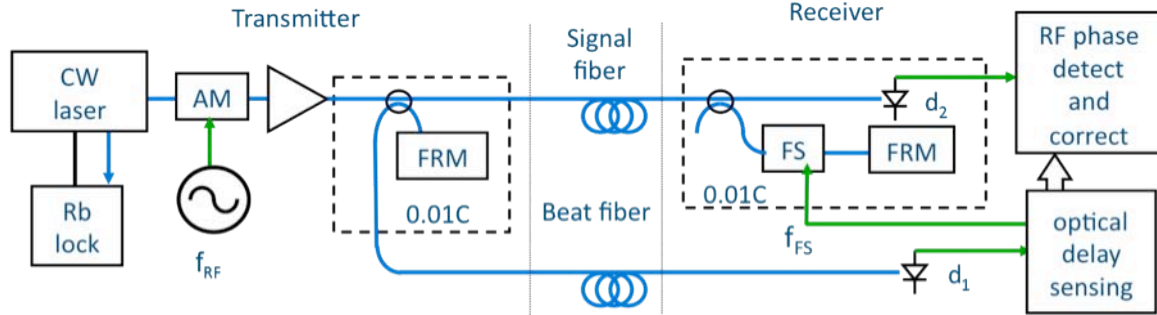


Figure 3: Schematic layout of a single channel RF transmission over an optical link. RF frequency is 2850MHz. AM: Amplitude modulator; FRM: Faraday rotator mirror; FS: optical frequency shifter. Dotted rectangles indicate components temperature controlled to ± 0.01 C.

along with the amplitude-modulated RF signals to be stabilized. The measured optical phase shift is used to correct the detected RF phase. To compensate for the difference between phase and group delay in the fiber, an additional correction is applied.

Each fiber link is one arm of a heterodyne Michelson interferometer. The reference arm is a short fiber (about 1m) with its temperature stabilized to ± 0.01 C. An acousto-optic frequency shifter at the receiver end of the long arm shifts the optical frequency by 100 MHz in two passes, adding its input 50 MHz RF phase to the optical phase. The beat between the reference and reflected optical carrier is detected as a 100 MHz RF signal whose phase is compared with twice the frequency-shifting signal. The RF phase shift of this 100 MHz signal is equal to the optical phase shift in the long arm, providing an increase in temporal sensitivity of 2×10^6 , the ratio of the optical to the beat frequency. Thus the 100 MHz beat signal can be sent back to the receiver over an unstabilized fiber, a novel feature of this scheme. The receiver then adjusts the frequency shifter RF phase to correct the optical phase, a function typically implemented in the transmitter[10]. This provides the ability to deliver a stable optical frequency over fiber.

The stability of our optical phase controller was verified by constructing a Mach-Zehnder interferometer out of two such heterodyne interferometers. One 2 km fiber was exposed to ambient temperature variation and a short 2 m fiber was in a temperature controlled environment. Diurnal temperature variations caused up to 2 ns delay changes in the 2 km fiber. After correction, the overall differential phase error between two stabilized links was six optical waves peak-to-peak over ten days[11].

For stable RF transmission, the CW laser used in the interferometer must have a fractional frequency stability less than the desired fractional temporal stability of the transmission delay. For a 2 km link with 10 fs stability,

this corresponds to $\Delta\lambda/\lambda = 10^{-9}$. The CW laser frequency is locked to a hyperfine absorption line in Rb vapor, achieving 5×10^{-10} .

A 2850 MHz RF signal is amplitude modulated onto the optical carrier by a lithium niobate modulator. The bias point is stabilized by detecting the second harmonic

of the 2850 MHz modulation in a phase-locked loop. Amplitude modulation depth is typically 70%, detected by a photodiode.

One issue with photodiode detection is amplitude modulation to phase modulation (AM-to-PM) conversion, where changes in the average optical power modulate the phase of the detected RF signal. The optical power level is set to a local maximum in the AM-to-PM photodiode response, where there is zero slope and minimal sensitivity to fluctuations in optical power. At this peak, a $\pm 10\%$ variation in average photocurrent causes less than 10 fs delay variation in the detected RF signal.

The receiver is a digital RF phase comparator used to compare the transmitted RF signal with a local signal to be controlled. Since the delay through coaxial cables and other RF components is temperature dependent, variations are corrected by subtracting a local calibration signal sent through both comparison paths. All processing of RF signals is done at an intermediate frequency of 50 MHz, after mixing down with a 2800 MHz local oscillator.

Due to the continuous nature of the signal, retroreflections anywhere in the fiber optic signal path can cause random fluctuations of the received RF signal phase. The measured RF signal is the vector sum of the desired signal and an interference vector whose relative angle is determined by the physical spacing of the reflections, and whose amplitude is determined by the relative optical phase of the signal and retroreflection. This relative optical phase varies rapidly with temperature, in the case of widely spaced reflections. As the amplitude of the interference vector changes, the received RF phase and amplitude vary. To suppress these effects to below 10 fs, all optical reflection losses need to be greater than 40 dB, so angle polished connectors (APCs) and high return loss components are used.

We initially characterized the performance of this system in our lab by measuring the relative time

difference between long and short stabilized links. These results are described in detail elsewhere[9]. In summary, we measured an RMS deviation of <10 fs on a 200 m fiber for over 20 hours and <20 fs on a 2.2 km fiber over

60 hours. The results of this system installed in the LCLS are described in the next section.

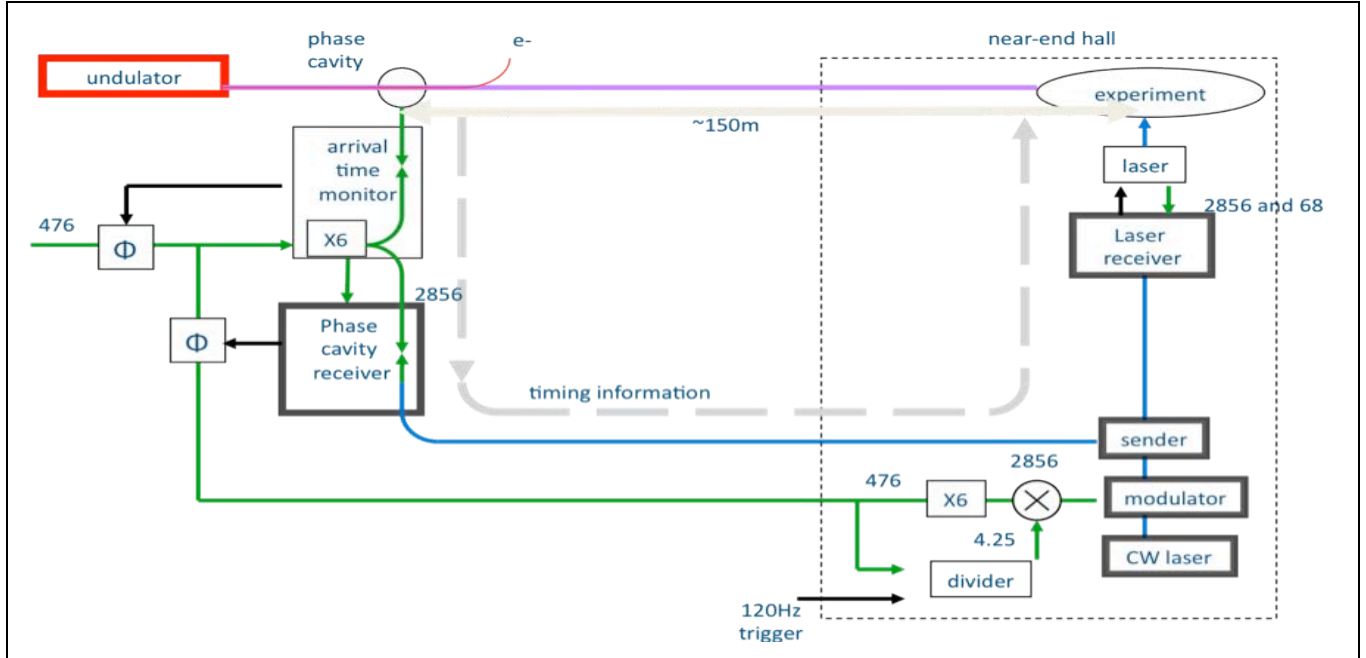


Figure 4. Detailed schematic of the signal path for synchronizing the user laser with the arrival time diagnostic (phase cavity.) The 150 m stabilized link to the phase cavity locks the optical distribution system to the average arrival time of the beam as determined by the phase cavity. Shot-to-shot variations of the beam arrival time with respect to the average are recorded and used by the experiment to sort the data in post-processing.

LCLS RESULTS

A schematic of the installation of a 2-channel synchronization system is shown in Fig. 4. The aim of this system is to synchronize the arrival time of the x-ray pulse with the user laser pulse. In the LCLS, the arrival time of each electron bunch is measured with a phase cavity. Note that the arrival time of the x-ray pulse is not necessarily the same as that of the electron bunch.

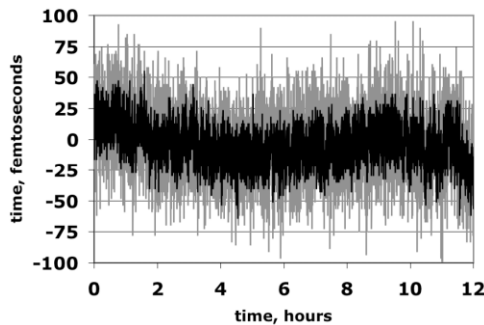


Figure 5: Relative drift of a 2856 MHz signal transmitted over the phase cavity link (2x150m) and the laser fiber (5 m) fiber. The relative time difference has an RMS deviation of 16 fs in a 1 kHz bandwidth over 12 hours. The slow drift is due to an 0.5 m unstabilized cable between the two receivers.

The phase cavity is a resonant cavity with a frequency of 2805 MHz and a Q of a few thousand. As the beam passes through the cavity, it excites a transient oscillation. The relative phase of this oscillation is compared with the phase of a 2856 MHz clock multiplied up from the 476 master oscillator signal for the LCLS. A servo loop adjusts the phase of the 2856 MHz signal such that the average beam arrival time is at the zero crossing of this clock. The relative timing of each electron bunch is measured with respect to the average arrival and reported to the user for post-processing of their data.

The fiber link transmitter is located in the first of the LCLS user areas (Near End Hall), a few meters from the user laser system. The entire transmitter and one of the receivers occupies about 2/3 of a standard 19-inch rack. One of the fiber links runs a few meters to the nearby laser. The other link runs ~150 m to the phase cavity in the linac tunnel just downstream from the undulator.

To lock the fiber links to the phase reference provided by the phase cavity, the fiber receiver adjusts the relative phase of the master clock so that the transmitted signal on the fiber links maintains a constant relative phase to the master clock.

To measure the relative stability of the two fiber links, we looped the fiber to the phase cavity back to the transmitter and compared the relative phase of the two

receivers as shown in Fig. 5. The RMS relative drift of the two links over a half day period was 16 fs. The slow drift seen in Fig. 5 is fully accounted for by the 0.5 m unstabilized cable connecting the two receivers.

The user laser is a mode-locked Ti:sapphire oscillator. A schematic of the layout for synchronizing the laser to the 2856 MHz reference phase is shown in Fig. 6. The phase of 7th harmonic of the laser signal observed on a photodiode in the oscillator, multiplied by 6, is compared with the reference phase. The error signal is used to correct the laser phase by driving a piezo-controlled mirror in the laser cavity. The in-loop laser control error signal over a day is shown in Fig. 7. The RMS signal over a 125 kHz bandwidth was 120 fs and over a 1 kHz bandwidth the value was 25 fs.

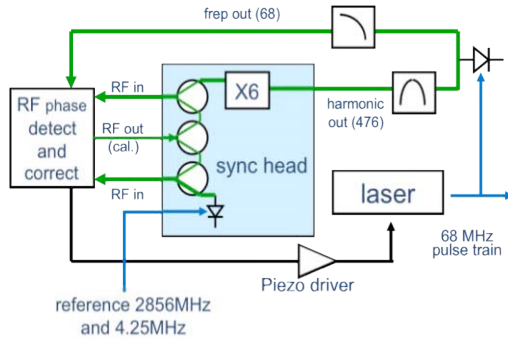


Figure 6: Schematic layout of synchronization to user laser oscillator.

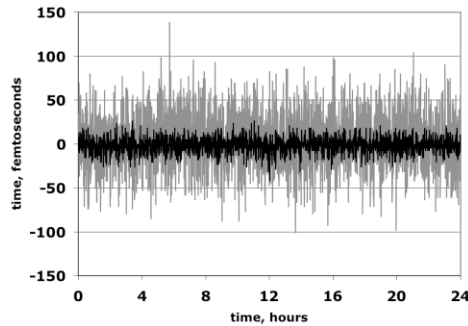


Figure 7: In-loop laser control error signal over a day. The RMS error signal was 120 fs over a 125 kHz bandwidth (gray), and 25 fs over a 1 kHz bandwidth (black).

This system was installed at the LCLS in September 2009 and ran continuously during the first LCLS user run in October 2009.

CONCLUSION

We have installed a fiber link system at the LCLS for high precision distribution of RF signals used for synchronization of a user laser with the average arrival time of the electron beam as measured with a phase

cavity. We were able to regularly achieve an rms jitter and drift between two RF channels of less than 20 fs.

We locked one of the two links to the reference phase provided by the phase cavity and the other link to the mode-locked Ti:sapphire oscillator.

We achieved a 25 fs relative locking stability to the laser in a 1 kHz bandwidth. We expect to improve the stability by improving the laser pump stability and vibration isolation of the oscillator.

The fiber synchronization system operated continuously during the LCLS user run in Oct 2009 and is presently in use for the run that began in mid-April 2010. LCLS is engineering production receivers (8 channels) and upgrading the transmitter to 16-channel capability

This approach has several advantages for operation in an accelerator facility. It is easily manufacturable, expandable to many channels, and can be configured to lock to a wide variety of clients. Following the demonstration of this two-channel system, the first commercially produced subsystems are presently being tested.

We are planning several activities over the next year. These include improving the laser oscillator stability and control, transmitting higher frequencies for higher phase resolution. We also plan a full series of measurements to characterize the overall timing stability of the x-ray and laser pulses.

REFERENCES

- [1] C. Pellegrini, "Overview Of Single Pass Free Electron Lasers," in Proceedings of the 10th European Particle Accelerator Conference (EPAC 06), Edinburgh, Scotland, 26-30 Jun 2006.
- [2] A. M. Lindenberg, et al. "Atomic-scale visualization of inertial dynamics," *Science* 308, 392 (2005).
- [3] A. L. Cavalieri, et al. "Clocking Femtosecond X Rays," *Phys. Rev. Lett.* 94, 114801 (2005).
- [4] O. Lopez, A. Amy-Klein, C. Daussy, Ch. Chardonnet, F. Narbonneau, M. Lours, and G. Santarelli, "86-km optical link with a resolution of 2×10^{-18} for RF frequency transfer," *Euro. Phys. J. D* 48, 35 (2008).
- [5] P. A. Williams, W. C. Swann, N. R. Newbury, "High-stability transfer of an optical frequency over long fiber-optic links," *J. Opt. Soc. Am. B* 25 1284 (2008).
- [6] H. Kiuchi, "Highly Stable Millimeter-Wave Signal Distribution with an Optical Round-Trip Phase Stabilizer," *IEEE Trans. Microwave Theory and Tech.*, 56, 1493 (2008).
- [7] D. D. Hudson, S. M. Foreman, S. T. Cundiff and J. Ye, *Opt. Lett.* 31, 1951 (2006).
- [8] J. Kim, J. A. Cox, J. Chen, F. X. Kartner, "Drift-free femtosecond timing synchronization of remote optical and microwave sources," *Nature Photonics* 2, 733 (2008).
- [9] R. Wilcox, J. M. Byrd, L. Doolittle, G. Huang, and J. W. Staples, "Stable transmission of radio frequency signals on fiber links using interferometric delay sensing," *Opt. Lett.* 34, 3050 (2009).

- [10] J. Ye, J.-L. Peng, R. Jason-Jones, K. W. Holman, J. L. Hall, D. J. Jones, S. A. Diddams, J. Kitching, S. Bize, J. C. Bergquist, L. W. Holberg, L. Robertsson, and L.-S. Ma, "Delivery of high-stability optical and microwave frequency standards over an optical fiber network," *J. Opt. Soc. Am. B* 20, 1459 (2003).
- [11] J. W. Staples, J. M. Byrd, L. Doolittle, G. Huang, and R. Wilcox, "A Femtosecond-Level Fiber-Optics Timing Distribution System Using Frequency-Offset Interferometry," *Proceedings of the 2008 Linear Accelerator Conference*, M. Comyn, ed. (IEEE, 2008).
- [12] A. Bruner, V. Mahal, I. Kiryushev, A. Arie, M. A. Arbore, M. M. Fejer, "Frequency stability at the kilohertz level of a rubidium-locked diode laser at 192.114 THz," *Appl. Opt.* 37, 6410 (1998).
- [13] S. Masuda, A. Seki, S. Niki, "Optical frequency standard by using a 1560 nm diode laser locked to saturated absorption lines of rubidium vapor," *Appl. Opt.* 46, 4780 (2007).
- [14] F. X. Kartner, H. Byun, J. Chen, F. J. Grawert, F. O. Ilday, J. Kim, and A. Winter, "Progress in Large-Scale Femtosecond Timing Distribution and RF-Synchronization," in *Proceedings of the 2005 Particle Accelerator Conference*, C. Horak, ed. (IEEE, 2005).